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Simulation of Rigidly-Linked Nanosatellites

Arnaud Lecuyot[a,b], Stephen Hobbs[b], Ian Honstvet[a]
[a]EADS Space Astrium Ltd, Stevenage, U.K.
[b]Space Research Centre, School of Engineering, Cranfield University, U.K.

Abstract

Rigidly linked nanosatellites are simulated as part of a PhD research on a new concept of space structure. Applications include a 1D interferometer in Earth and Lagrange orbits and a 3D Solar concentrator in Earth and Moon orbit. Simulation methods include a link tension derivation based on tether dynamics, and a simple On-Off constant thrust nanosatellite controller. Results show the basic controllability of most proposed applications. At system design level, the controller does not provide adequate lifetime in its current form, but the concept is in principle feasible.

Introduction

This article reports on a simulation campaign addressing the dynamics of space structures comprised of rigidly linked nanosatellites. It is part of a more wide-ranging research on applications and design of such systems, called metastructures [1]. A concept background and definition summary is given below.

Concept background

Structure design for large space systems is essentially an *ad hoc* activity, where each solution is customised to a particular problem. However when considered from a systems engineering point of view, one can identify classes of structures against size and applications [2]. At the lower end of the size range are the “traditional” rigid deployables designs, such as the Hubble Space Telescope. At the other end are “virtual”, formation-flying structures. In the middle are a number of possible configurations, from flexible deployables, to inflatables, to so-called “smart structures”.

A particular configuration not yet developed is that of using active linked nodes to “discretise” a structure into individual elements, on which a distributed system architecture and control is applied. This concept is called a *metastructure*, illustrated in Figure 1 below. There are several possible implementations of this concept, but the one considered here is that of rigidly linked nanosatellites. Nanosatellites will use applications of Micro and Nanotechnology to spacecraft engineering [3] to produce highly integrated miniature satellites, lower than 1 kg in mass and about 10 cm in size. When linked with carbon nanotube [4] composite rigid beams, they may result in systems that can deploy large structures in space (up to 1000 m on each side).

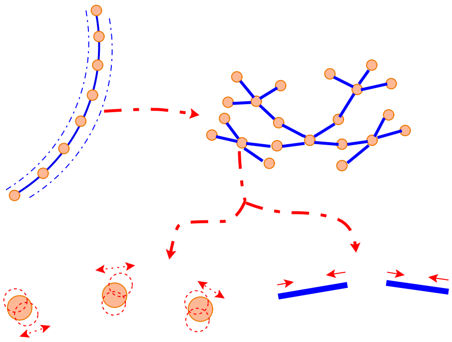


Figure 1: Metastructure concept: many linked elements are actively controlled to give the resulting structure its desired geoemtry.

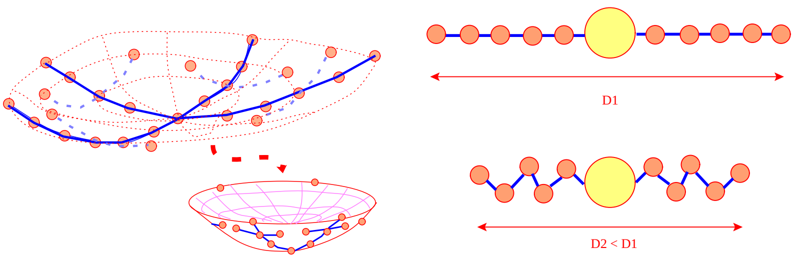
Metastructures as rigidly linked nanosatellites

As part of a concept evaluation research, a dynamics analysis of such systems is conducted to assess their behaviour sensitivity, controllability, and impact on system and subsystem design. Features considered for simulation are:

- There are two types of nanosatellites: *Local*, able to control its position relative to their neighbours, and *global*, controlling its position in an inertial frame.
- These are organised in repeating patterns. A pattern in a 1D structure can for instance be 2 locals, 1 global, and 2 locals (L-L-G-L-L), and repeated as necessary (LLGLL-LLGLL-LLGLL for 3 patterns).
- One reference mission is an interferometer, based on an accordion-like configuration that can change shape to adjust baseline. It is as shown in Figure 2(a) below. It can be used in large wavelength astronomy [5].
- The other reference mission is a so-called Solar concentrator, considered as part of a Solar or Lunar Power system [6]. It is a large parabolic reflector that needs to maintain a 3D shape, as seen in Figure 2(b) below.

Simulation methods

The dynamics problem at hand thus considers a number of rigidly linked nanosatellites as nodes in a matrix arrangement. The modelling methods for simulation of this rely on the reduction of the problem, the derivation of a tension matrix for the rigid links, and a controller design for the nanosatellites. These are considered next, together with the selection of the cases to be simulated.



(a) (b)

Figure 2: Applications of the concept considered: (a) Interferometer, (b) Solar concentrator.

Dynamics problem reduction

Similar classes of problems have been addressed in the study of the dynamics of tethered space systems [7]. The selected approach reduces the problem by considering simplifying assumptions:

Links are rigid: This is in fact not a simplifying hypothesis, but a consequence of system design.

Joint are perfect: The revolute joints between the links and the nodes are perfect, the main impact being that there is no friction force.

Controllers are perfect and multi-directional: There are no time delays and no errors in measurement. Also, the thrust generated has two components; One in the plane perpendicular to the link, and the other one along the link.

Environment is a Newtonian field in circular orbits: All perturbation forces of the space environment are ignored. Also, both reference missions use circular orbits, so the second assumption is not restrictive.

Nodes have same mass which is true to first order.

Tension matrix derivation method

This method is an extension of a rigid tether model developed previously [8]. It differs when the matrix $[A]$ is derived (see below), which is a part of this work that is novel. Using the rigid link assumption, the distance between two nodes is maintained, i.e. for two nodes of the matrix (i, j) and $(f,g) = (i, j) \pm 1$ linked,

$$|\mathbf{R_{i,j}} - \mathbf{R_{f,g}}| = Cst$$

the constant value Cst being the length of the nodes. By manipulating the system of equations for all nodes, it can be expressed as a matrix equation of the tension forces vector matrix $[T]$ such that

$$[A]\cdot[T]=[B]$$

with $[B]$ a vector matrix representing the external forces and terms related to the relative centrifugal forces of the linked nodes. In a tether model, the other matrix $[A]$ would be a diagonal matrix with non-zero terms only in (i,i), $(i-1,i)$ and $(i+1,i)$ as each node is connected with only two other nodes. For the current case though, the terms are different, and the terms $A(i,j)$ can be expressed as

$$A(i,j)=\Delta\mathbf{R}\cdot\mathbf{a_{i,j}}$$

which is a vectorial cross product, where $\Delta\mathbf{R}=\mathbf{R_{i,j}}-\mathbf{R_{f,g}}$, and $\mathbf{a_{i,j}}$ is a unit vector or a null vector. It depends on the e_{ij}, which is itself the unit vector parallel to a tension vector at node (i,j). So $\mathbf{a_{i,j}}$ is such that:

$$\mathbf{a_{i,j}}=\sum_{(i,j)}(\alpha_{i,j}\cdot\mathbf{e_{i,j}})$$

with coefficients $\alpha_{i,j}=0|+1|-1$, if the nodes are respectively not connected, directly linked (rightwards or downwards), or indirectly linked (leftwards or upwards). The matrix equation can be solved using linear algebra.

Controller modelling method

The basis for controller choice is simplicity of implementation. The chosen controller's output depends on the position (e_p) and velocity errors (e_v) for each satellite, refers to an error deadband e_{max} and v_{max}, has fixed thrust F and uses a +1/-1 switch, the law of which is according to a "phase plane" derivation [9]. The control action is $u=\beta\times F$ with β such that:

$$\begin{array}{ll}
\beta=0, & \text{if } e_p<e_{max};\\
\beta=+1, & \text{if } e_p>e_{max} \text{ and } e_v>v_{max};\\
\beta=+1, & \text{if } e_p>\frac{(e_v)^2}{2} \text{ and } e_v<v_{max};\\
\beta=-1, & \text{otherwise.}
\end{array}$$

Cases selection, development and validation

Cases considered include validation cases for tether and controller dynamics, and a number of uncontrolled and controlled reference structure cases. The reference *structure* is a test case used to explore dynamics. It is in Earth circular orbit at 1000 km. The interferometer reference *mission* is also simulated, considered in freefall (i.e. Lagrange orbit) and in Earth orbit at 500 km. Finally the Solar concentrator reference mission is considered, in Earth orbit at 6000 km circular orbit.

A custom simulator software is built for this called *UniSim* (as it is in principle extensible to other environments). It is implemented using the Python scripting language with associated numerical analysis libraries. It is validated against controller implementation and tether dynamics simulation [1].

Simulation Results

Reference structure

Uncontrolled dynamics of the reference structure show clearly that the drift from the correct position grows significant [1], so control is necessary. The basic performance of a reference structure with controlled nanosatellites is as shown in Figure 3. It is shown that for a single pattern of the structure, controllability is possible.

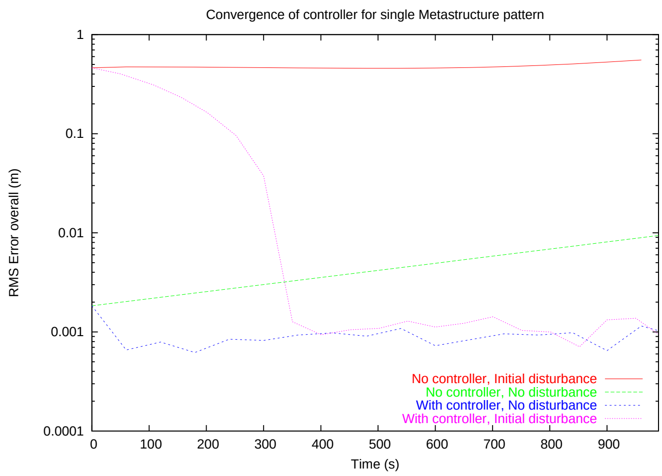


Figure 3: Controller performance for an initially disturbed and undisturbed state for the reference structure. The disturbed state is an initial inclination of 15° in and out of plane. The Y axis represents the Root Mean Squared Position Error overall (in m).

For this reference structure, detailed analysis has been conducted by varying system parameters [1]. In summary, the effects identified are such that:

- The performance of the controller is best measured by considering the total Impulse of the thrusters, i.e. the amount of “thrust” (and thus propellant) used over time. After the initial reduction of a disturbed state, a stable regime is established to compensate for the drift of the individual nanosatellites.
- The nanosatellite thrust to mass ratio affects this total impulse, as well as the time taken to reduce initial disturbances.
- The controller deadband parameter on position error e_p is directly reflected in the positioning accuracy achievable.
- Finally, the superposition of patterns results in an expected addition of errors, with errors being propagated across the whole structure from the outer panels.

Interferometer

The interferometer reference mission relies mostly on the ability to control the configuration of the linked nanosatellites, such that the interferometric baseline can be changed. In Figure 4 it can be seen that it is possible to obtain adequate levels of control for a number of baseline changes; The $9/10^{th}$ change was not completed but it is thought that it would behave similarly to the others. Also investigated for the

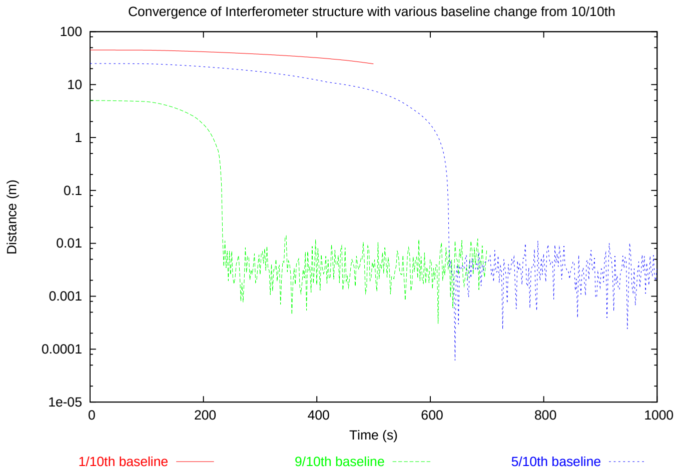


Figure 4: Convergence of the basic interferometer structure for a number of different baseline changes. The distance reported is the position error of the extreme nodes, forming the actual baseline.

interferometer are the variation in pattern definition and configurations with several patterns mounted in series. It is found [1] that with two or three patterns together the behaviour is similar (including positioning accuracy), whilst a single pattern with more global cells is likely to perform better than one with more local cells.

Solar concentrator

Finally, the Solar Concentrator case allows to test linked nanosatellites that maintain a 3D shape. A simulation with different controller types is shown in Figure 5. It can be seen that, apparently, relative cells are unable to maintain the shape. This is due to the fact that the centre of mass of such a structure is not located on the structure, thus leading to a wrong specification of the local reference point. This was not corrected in the course of the present analysis, but with global cells it is seen that a stable shape can be achieved.

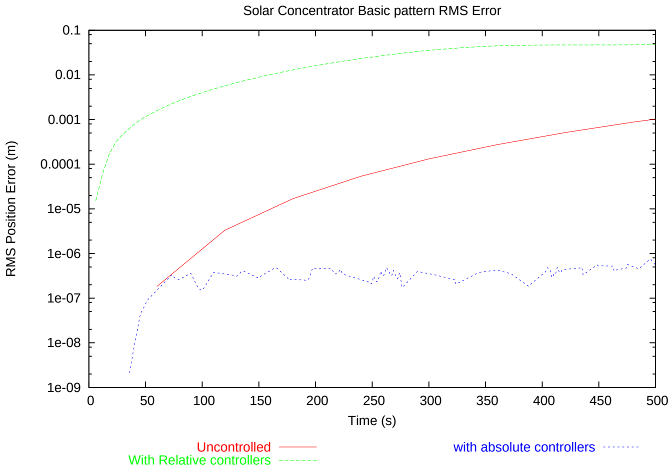


Figure 5: Solar concentrator results in Earth orbit by changing the basic cell type.

Discussion

The series of simulations performed give information on three accounts: The controllability of rigidly linked nanosatellites, the sensitivity of results to nanosatellite and system parameters, and the impact on the design of complete systems (i.e. metastructures). The accuracy of modelling assumptions is also considered.

Controllability

A controllable configuration can be found for each of the analysed missions, except for the interferometer considered in Earth Orbit (in a Lagrange Orbit it is controllable). Given that the nanosatellites, systems and missions modelled are aimed to represent the actual applications, it can be said the top-level feasibility of the concept is demonstrated. Further analysis in systems design [1] shows that the main drawback of the system considered is its short lifetime: The overall impulse can be close to that of a continuously thrusting nanosatellite, thus showing a high use of consumable propellant.

Results sensitivity

A summary of the results is as shown in Tables 1, 2, and 3. It can be seen that for nanosatellite parameters a correct ratio of thrust to mass can be found that will minimise the propellant use, although no formal analysis can at this time identify this relation. As regards pattern definition, a dependance of dynamic behaviour on pattern type is observed, but the simulation sample does not allow a precise definition of this phenomenon. Finally, it is also shown that a series of linked nanosatellites with several repeating patterns can also be controlled.

Orbit Height (km)	Node Mass (kg)	Cell Thrust (mN)	Error e_{max} (mm)	Normalised Impulse	RMS Error (m)
1000	0.01	0.1	1.0	5%	0.91
1000	0.1	0.1	1.0	N/A	1.0
1000	0.5	0.1	1.0	N/A	2.4
1000	0.01	1.0	1.0	58%	1.0
1000	0.1	1.0	1.0	N/A	0.9
1000	0.5	5.0	10.0	N/A	2.4
1000	0.5	5.0	1.0	N/A	0.61
10,000	0.01	0.1	1.0	58%	0.75
1000		2 patterns		60%	2.0

Table 1: Results summary for the reference metastructure. The Normalised Impulse represents the Impulse output of the simulation compared to the Impulse when thrusting all the time.

Environment	Node Mass (kg)	Cell Thrust (mN)	Normalised Impulse	Max Error (mm)
Free	0.01	10	34%	5.0
Free	0.01	5	48%	2.0
Free	Long links		48%	0.5
Free	More globals		48%	1.3
Free	2 patterns		N/A	2.5
Free	3 patterns		N/A	2.5
Earth	3 patterns		No Convergence	

Table 2: Results summary for the interferometer.

Environment	Node Mass (kg)	Cell Thrust (N)	Normalised Impulse	Max Error (m)
Earth	0.5	0.001	N/A	0.05
Earth	0.5	0.005	N/A	Similar
Moon	0.5	0.005	N/A	Similar

Table 3: Results Summary for the Solar Concentrator.

Impact on system design

The main impact on system and subsystem design is with respect to controller and nanosatellite design. As regards the distributed controller, it appears that the one used is far from optimal. Further research in distributed connected systems control [10] tends to show, however, that there exist specific controllers that can reduce the overall impulse used by the nanosatellites. But a clear result is that a significant amount of the nanosatellite mass has to be propellant.

As regards nanosatellite design, it appears that low levels of thrust used in simulations (0.1 to 5 mN) are compatible with microthruster subsystem designs. Equally, the needs for global or local positioning and control systems can be met with foreseen development of micro and nano technologies. There are even suitable devices currently in development (such as for instance micro star sensors [11] or magnetometres [12]).

Modelling assumptions discussion

For modelling, the hypotheses found to need review are mostly the assumed perfection of joints and controllers. Friction in particular is not taken into account, even though it can in principle be beneficial to the system design. As for the controller, it is evident that real controllers will have errors associated with them, but for the preliminary level of analysis here, these assumption are usually considered adequate. Another source of error that can also be investigated in further analyses is the non-Keplerian orbital effects, such as Solar Radiation Pressure, Earth Oblateness, or Lagrange environment gravity gradient effects.

Conclusions

In principle, it can be concluded that complex structures of rigidly linked active nanosatellites can be controlled and change shape for 1D, 2D or 3D structures in space. Considering some applications of such structures (called metastructures), simulations of such systems with adequate (i.e. realistic) parameters tend to show that such metastructures are worthy of further investigation. The simulation shows some insight into the behaviour of these structures in addition to demonstrating controllability, but further analysis may be done in order to identify the quantitative impact of system parameter variations.

Acknowledgments

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